



Plasma-Assisted Combustion Studies at AFRL

**MURI Kickoff Meeting
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Overview



Areas where plasmas and E-fields can have an influence

- Enhance reaction rate & flamespeed
 - Important for high-speed combustors (& other combustors too):
 - Ignition, from *cold* state especially & with liquid fuel
 - Steady operation, through flamespeed enhancement and flameholding
 - Potentially important for lean, gas-turbine (powerplant) operation
 - Might one also mitigate/influence acoustic fluctuations?
 - Potential for *uniform* performance with *nonuniform* fuel source
- Enhance fuel-air mixing & penetration
 - Potential alternative to intrusive mechanisms (struts/pylons)
 - Potential for dynamic control of penetration/mixing
 - Potential for creating recirculation region for flameholding
- Boundary-layer & surface interactions
 - Trip boundary layer; hold shock

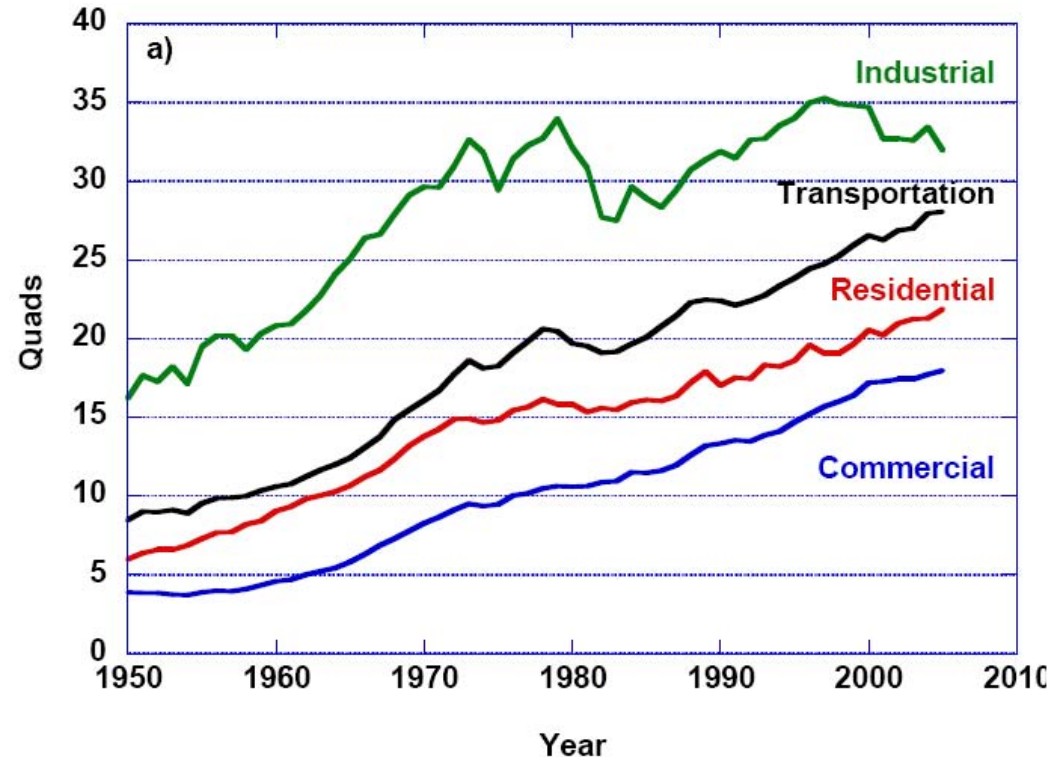


Overview

Fun Facts on US Energy Consumption

- HC sources provide ~85% of nation's energy
 - 97% for transportation
- Transportation's consumption about 28% of total
 - ≈ 1 million gallons/minute
- Quads = quadrillion (10^{15}) BTU
 $\approx 10^{18}$ J

US Energy Consumption, 1950-2005



Source: Energy Information Administration, Annual Energy Review 2005, Report DOE/EIA-0384 (2005).

See also *Report of the Basic Energy Sciences Workshop on Basic Research Needs for Clean and Efficient Combustion of 21st Century Transportation Fuels*

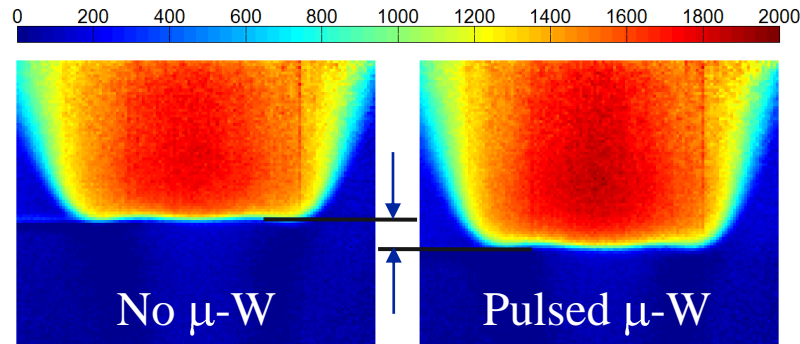


Overview

Plasma/E-field Effects on Ignition & Flame Behavior

μ -W E-field Effects on Flame Propagation

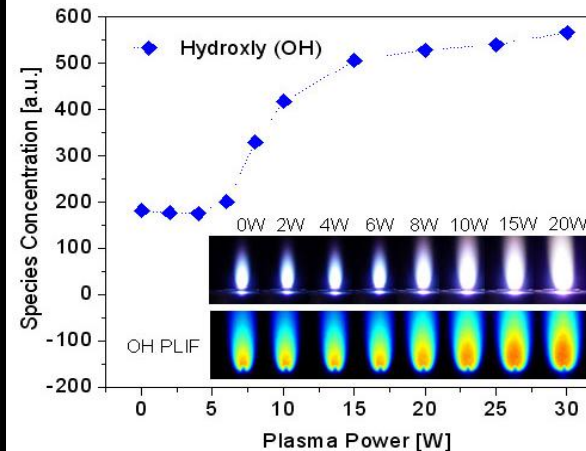
Stockman, Miles, Zaidi (Princeton), Ryan



Planar FRS Thermometry with pulsed μ -W Source

Diagnostics of Plasma Enhanced Flames

Lee (MSU)

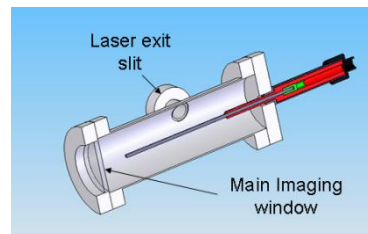
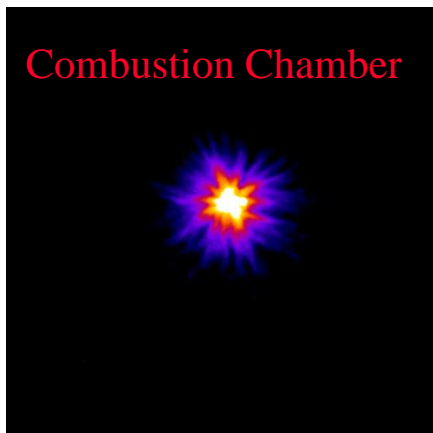


Direct coupled
plasma torch:
flame OH vs.
 μ -wave power:

Plasma-assisted Ignition

Cathey, Gundersen, Wang, Cain (USC), Ryan

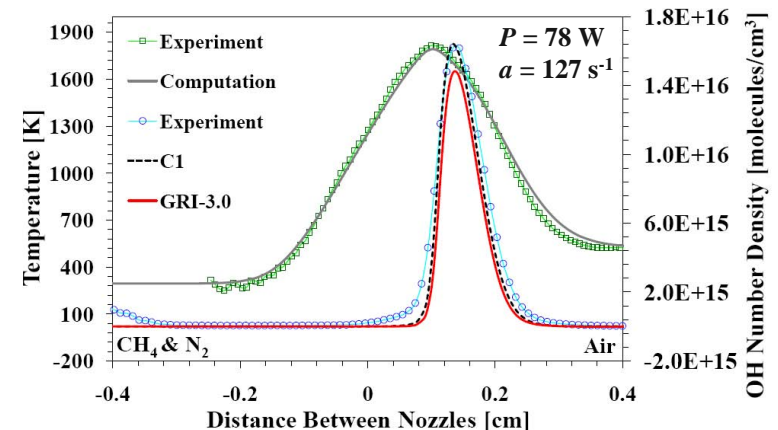
Combustion Chamber



Ignition event

Effects of Gliding Arc on Flame Chemistry


Ombrello, Ju (Princeton), Gutsol, Fridman, (Drexel)

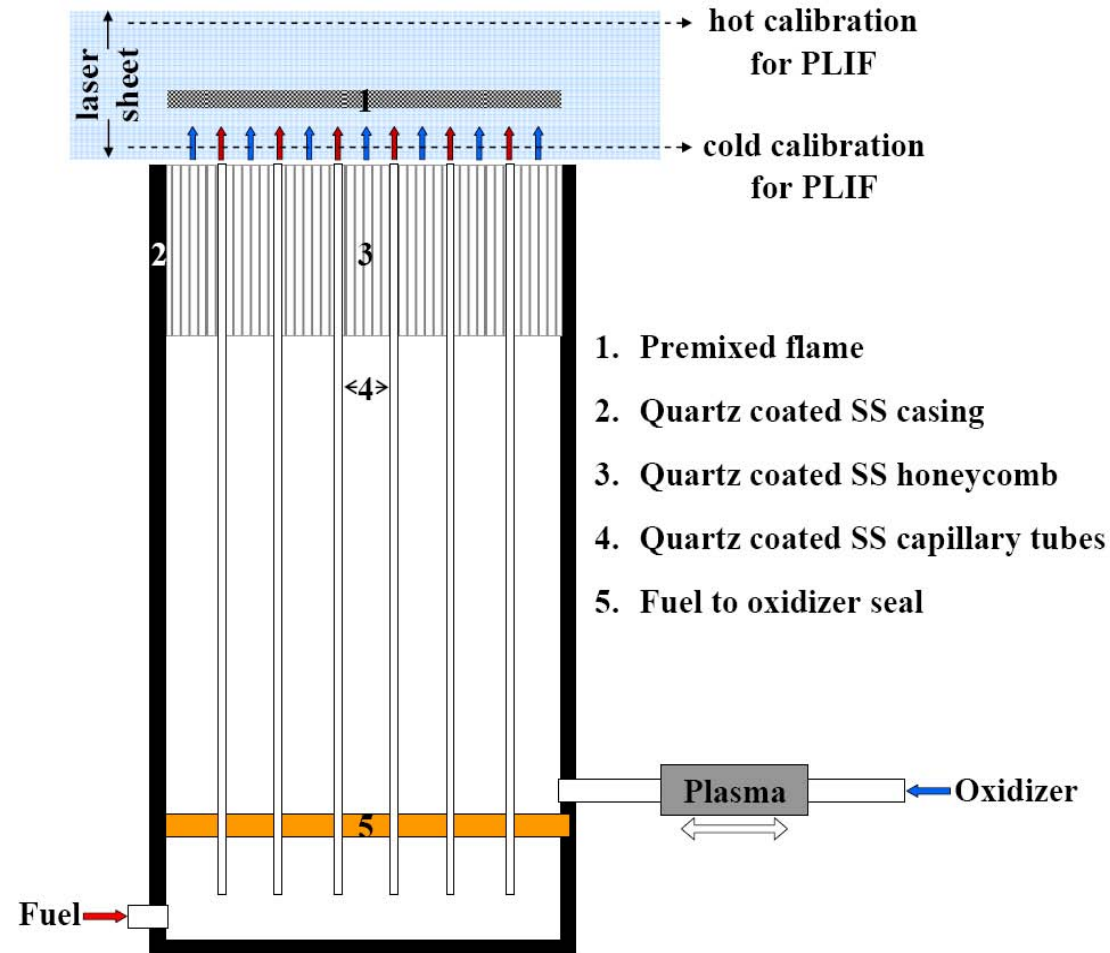




Enhancement of Flamespeed through Plasma Activation*

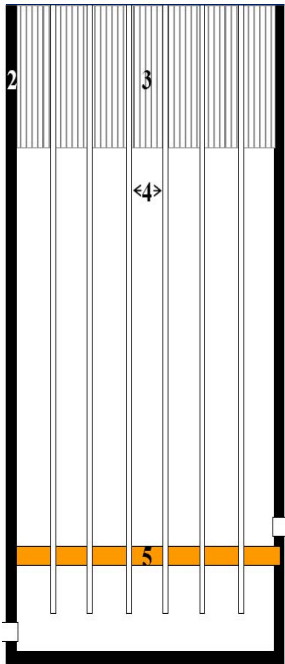


- **Goal:** Study flame propagation increase with plasma-excited oxidizer
- Integrate plasma source with custom *Hencken* burner 
 - Gases mix at burner exit
 - Quartz coating of metal surfaces
- Operate at low P
 - Reduced reaction rates
 - Allow mixing of fuel & oxidizer upstream of flame





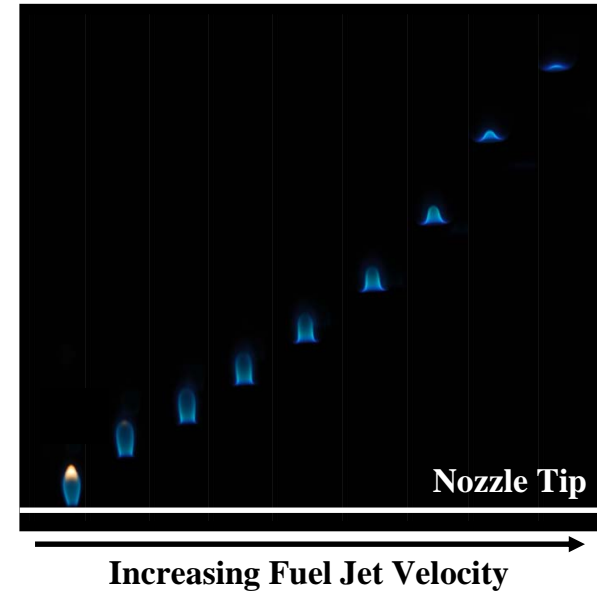
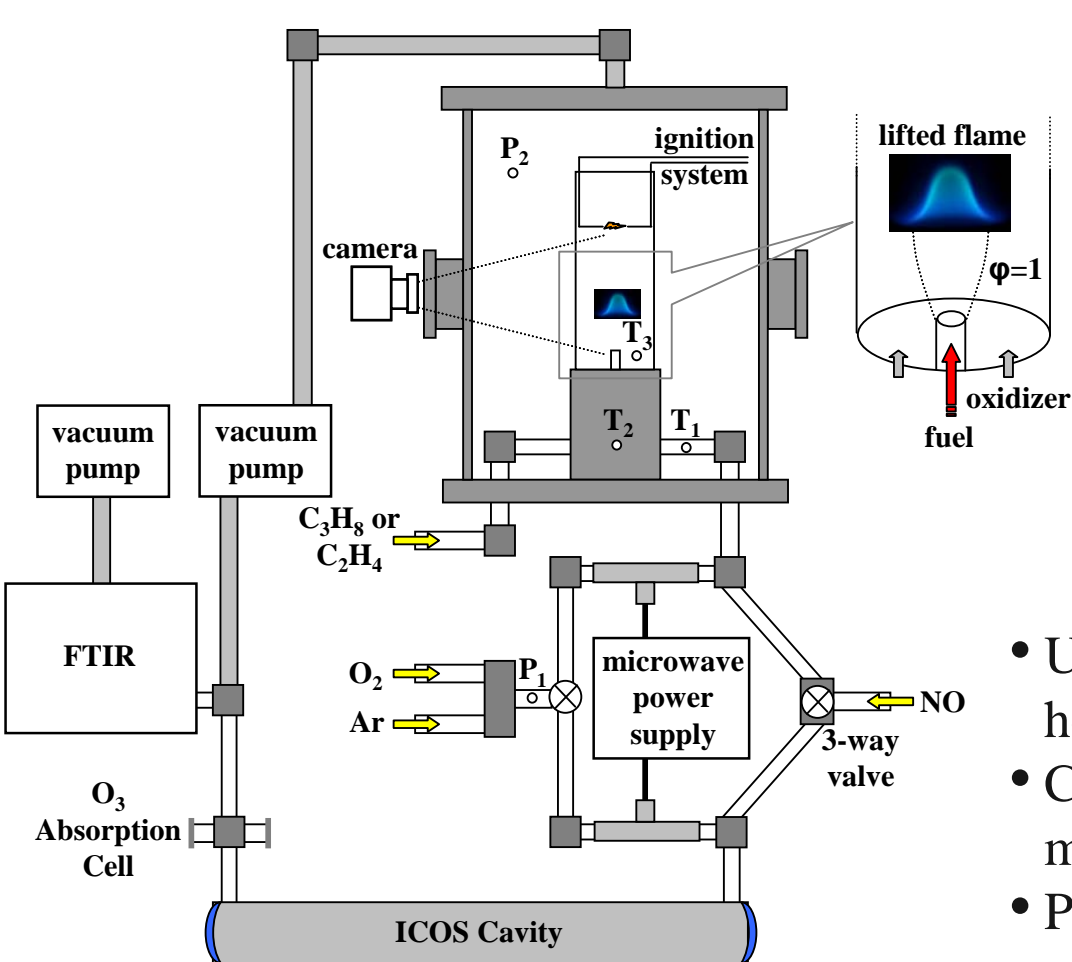
Enhancement of Flamespeed through Plasma Activation*



- Decrease chamber P to lift flame from surface
 - Flame has fully premixed character at low P
- Apply diagnostics to characterize plasma species, T & V
 - Species of interest: O_3 , $\text{O}_2(\text{a}^1\Delta_{\text{g}})$, $\text{O}_2(\text{b}^1\Sigma_{\text{g}})$, O , $\text{O}(\text{D})$



Enhancement of Flamespeed through Plasma Activation*



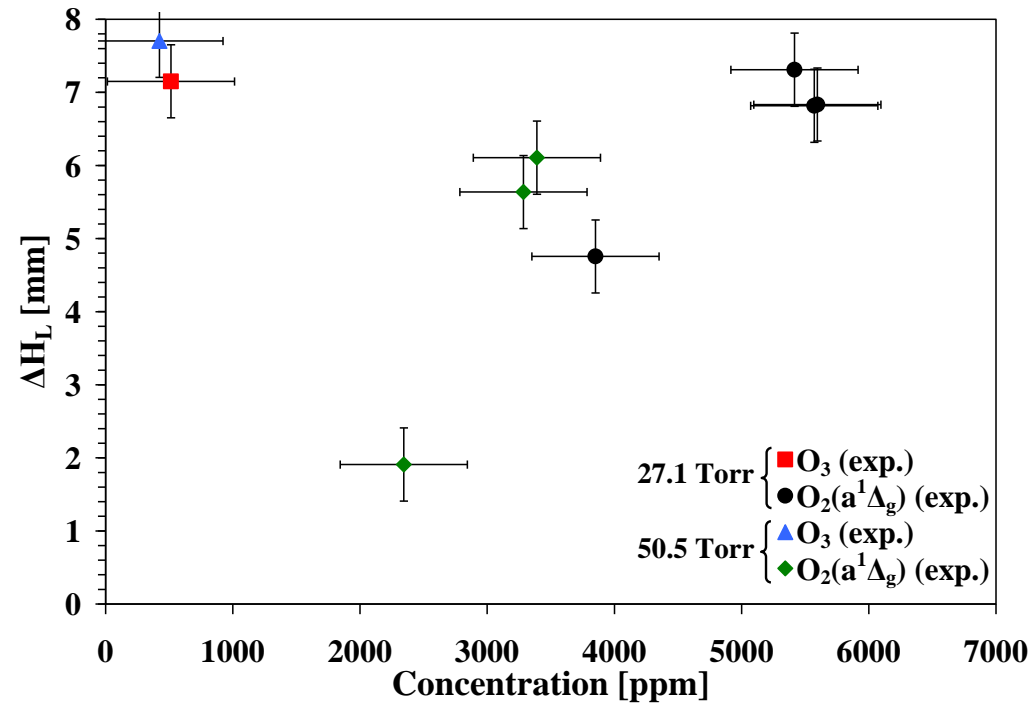
- Use low- P lifted jet flame: lift-off height ΔH_L sensitive to flamespeed, S_L
- Characterize S_L increase with ΔH_L measurement
- Produce & quantify O_3 and $O_2(a^1\Delta_g)$
 - measure ΔH_L



Enhancement of Flamespeed through Plasma Activation*



- Graph shows isolated effect of O_3 and $O_2(a^1\Delta_g)$
 - $P = 27$ or 51 Torr
- Concentrations of $O_2(a^1\Delta_g)$ as large as $\sim X = 0.6\%$
- Conversion of ΔH_L to S_L requires additional measurements and/or modeling
- Work with Hencken flame will be follow-on effort

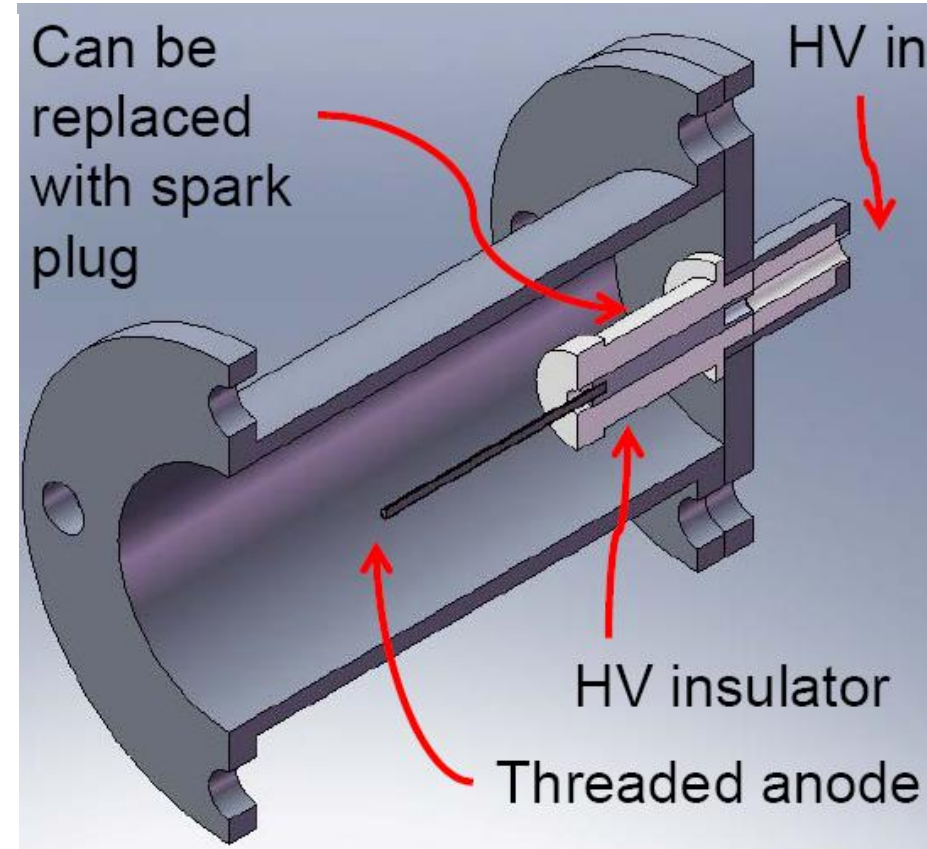




Ignition Enhancement with Transient Plasma (TP)*



- **Goal:** Determine physical mechanism, primarily for *transient plasma* ignition
 - What is role of humidity: $X_{\text{H}_2\text{O}}$ affects detonation wave speed in PDE but not t_{ign}
- Measure X_{OH} and X_{O_3} vs. $X_{\text{H}_2\text{O}}$ in air
 - OH from PLIF & O_3 from absorption
 - Need to sample along anode, especially since flame originates from anode surface
- Highly desirable: O-atom distribution
 - Also CH_3 and CH_2O

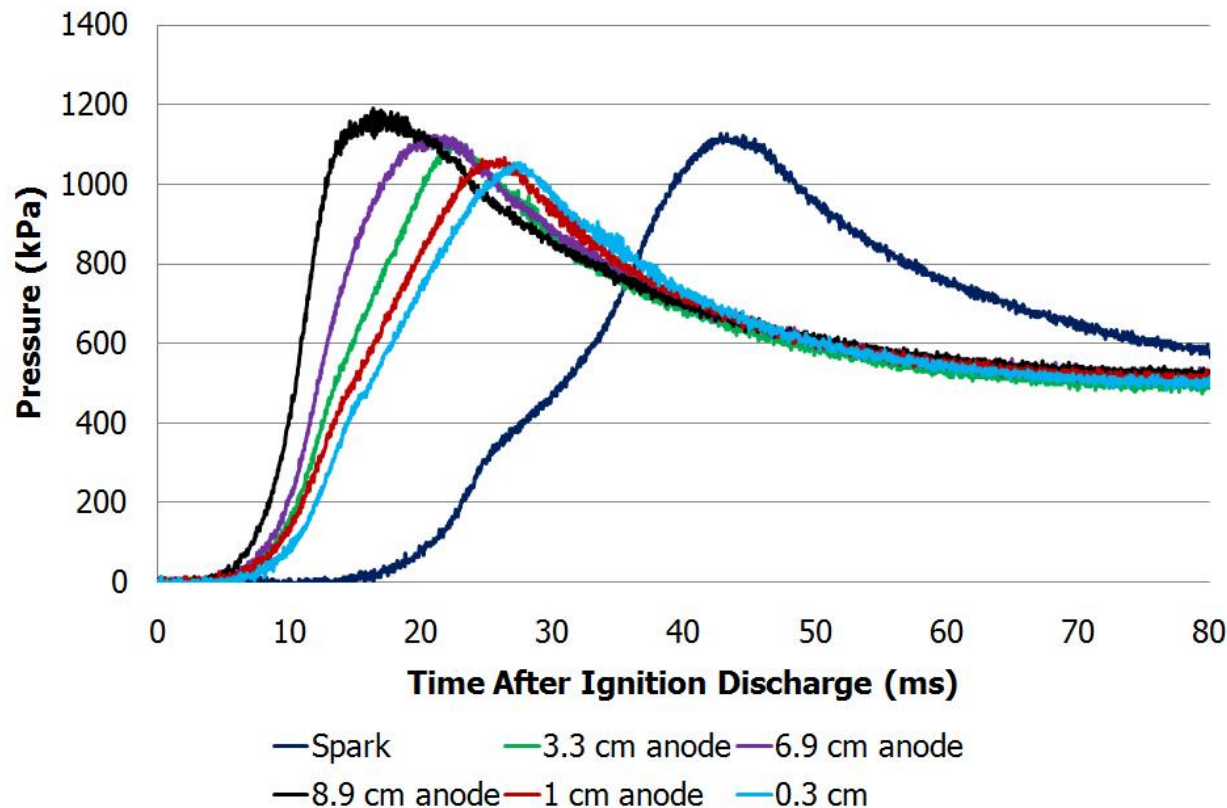


Combustion chamber

- Variable anode lengths & materials
- Optical access: windowed-slits (not shown) & end-flange window



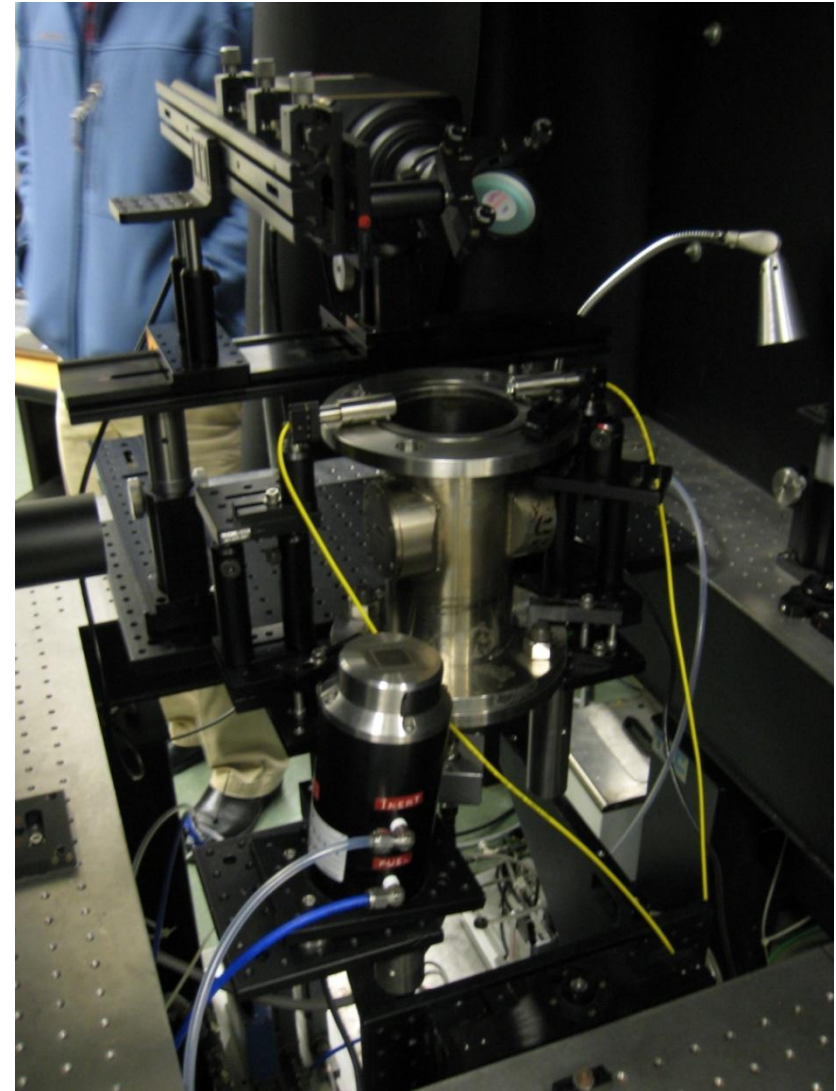
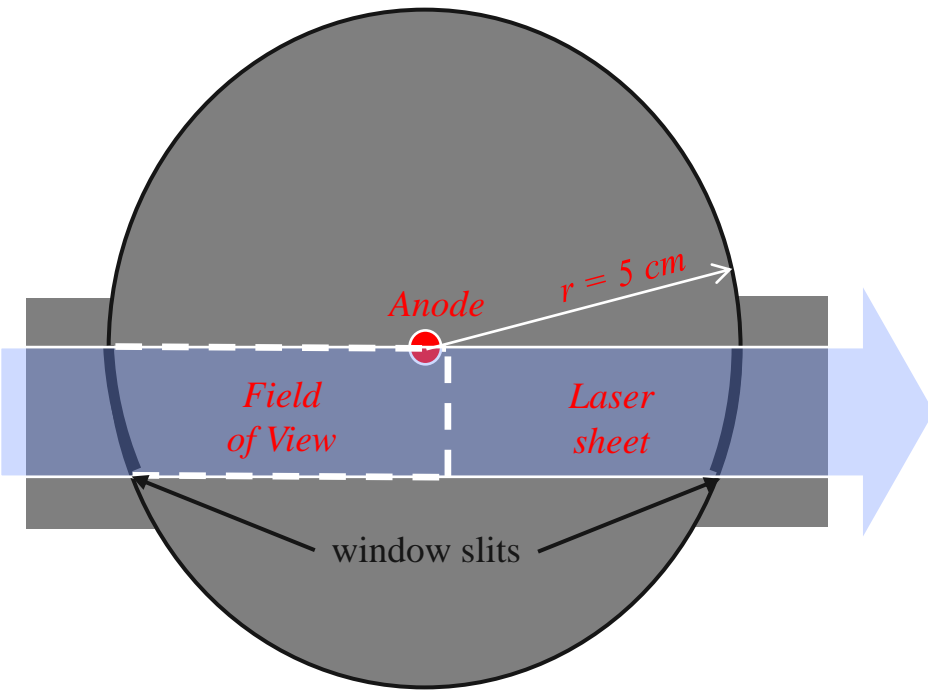
Ignition Enhancement with TP*



- Effect of anode length & comparison to spark plug (2 cm from back wall)
 - Significant reduction in t_{ign} even with 3-mm length protrusion
- Flame propagates from anode to wall
 - Flame initiation and propagation approx. uniform along perimeter & length



Ignition Enhancement with TP*

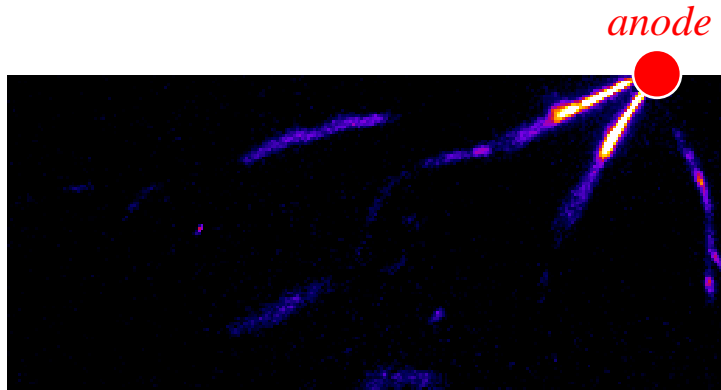


- Camera looking down into chamber
- Continuous flow of moist air
 - 1-Hz pulse frequency
 - $X_{\text{H}_2\text{O}}$ measured with TDLAS
- PLIF of OH: Peak signals $\sim 10^{15} \text{ cm}^{-3}$

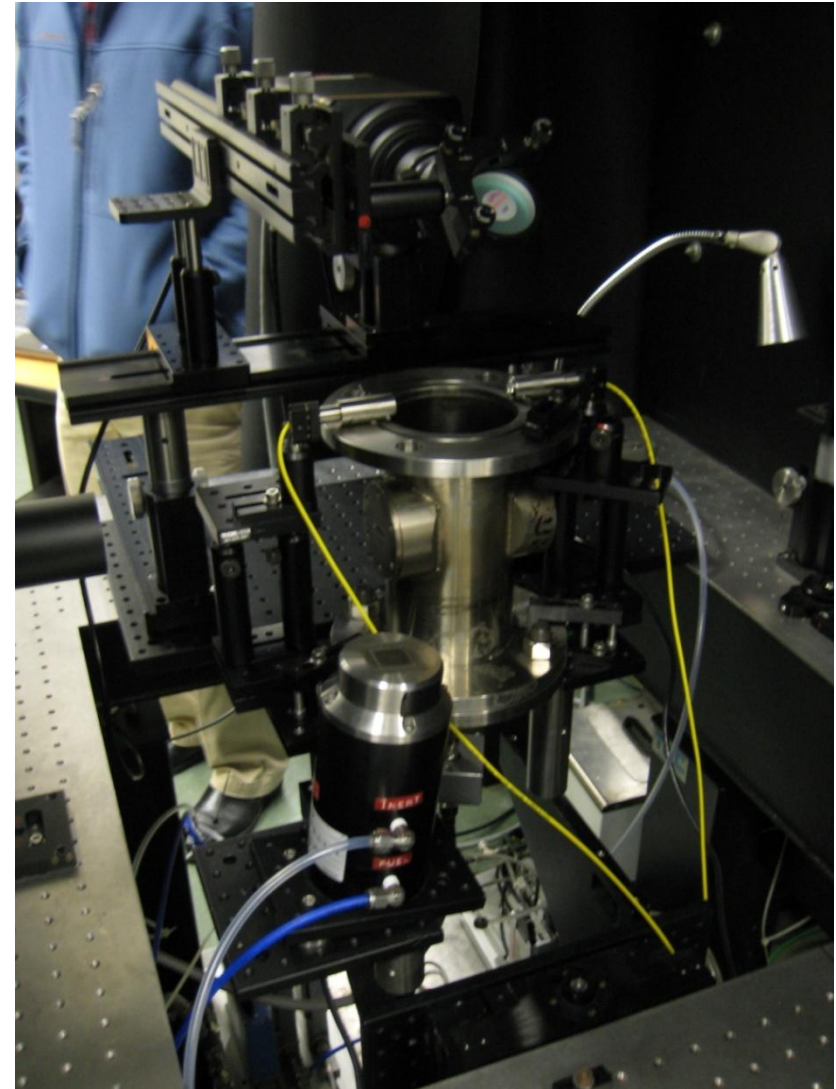
*Singleton, Pendleton, Gundersen (USC), Stockman, Carter, Brown



Ignition Enhancement with TP*



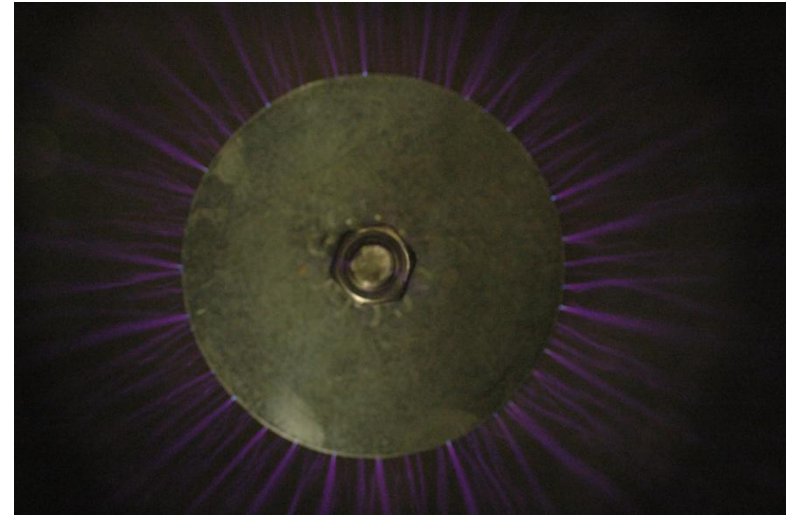
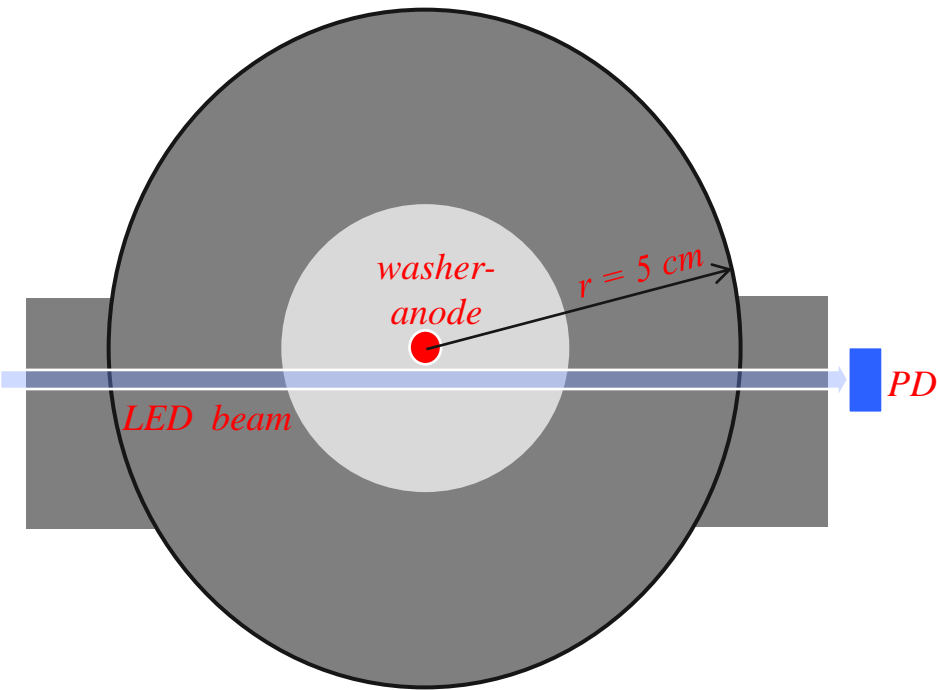
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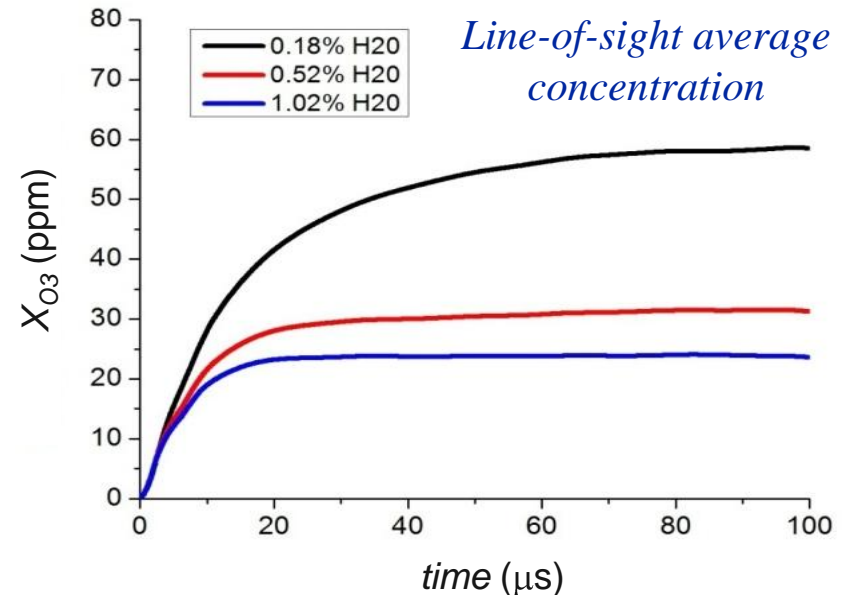
*Singleton, Pendleton, Gundersen (USC), Stockman, Carter, Brown



Ignition Enhancement with TP*



- UV LED beam positioned over washer
 - Undetectable X_{O_3} with normal config.
- 1-ms LED pulse synched to TPI pulse
 - 200 o-scope waveforms recorded
 - Presumably, X_{O_3} distribution nonuniform



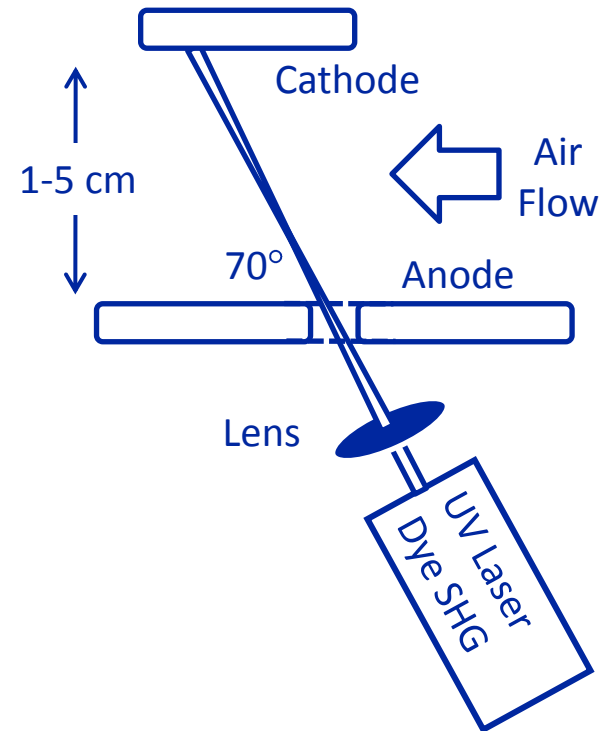
*Singleton, Pendleton, Gundersen (USC), Stockman, Carter, Brown



*Resonant Laser Induced Breakdown for Fuel-Air Ignition**



- **Goal:** Investigate effectiveness of low-energy REMPI laser pulse to control spatial & temporal behavior of ignition spark in air crossflow
- **Approach:**
 - Apply potential (below breakdown value)
 - Focus UV laser pulse at REMPI transition & ionize channel between gap



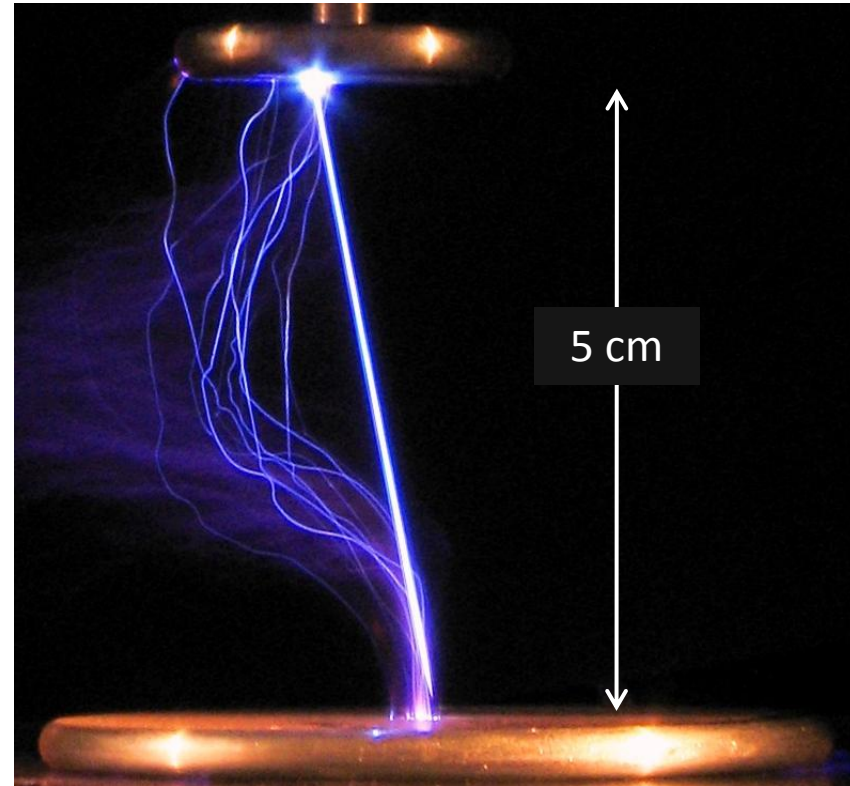
To be presented at ASM-2010



*Resonant Laser Induced Breakdown for Fuel-Air Ignition**



- Sample photo of a laser induced arc
 - Main arc follows laser path
 - Secondary arcs & plasma glow occur after main arc; result of leakage current as capacitor recharges



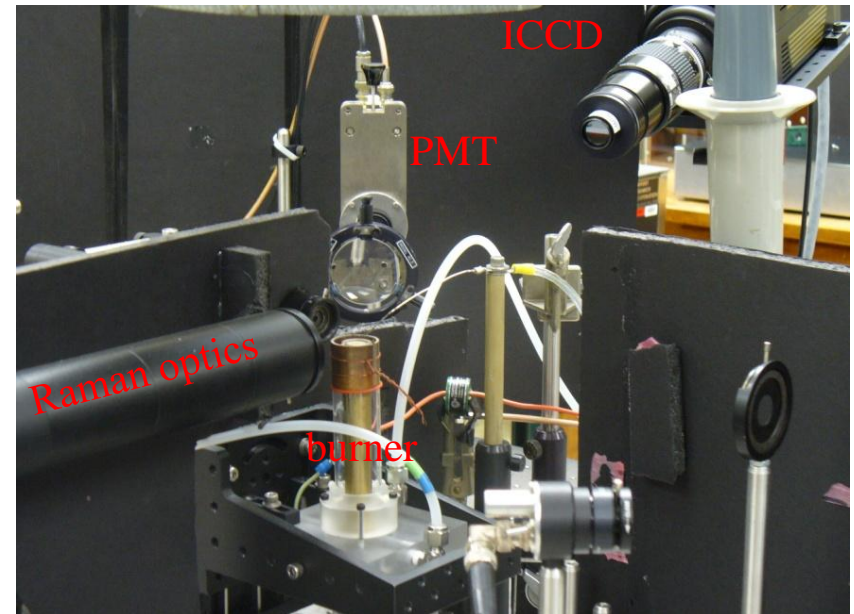
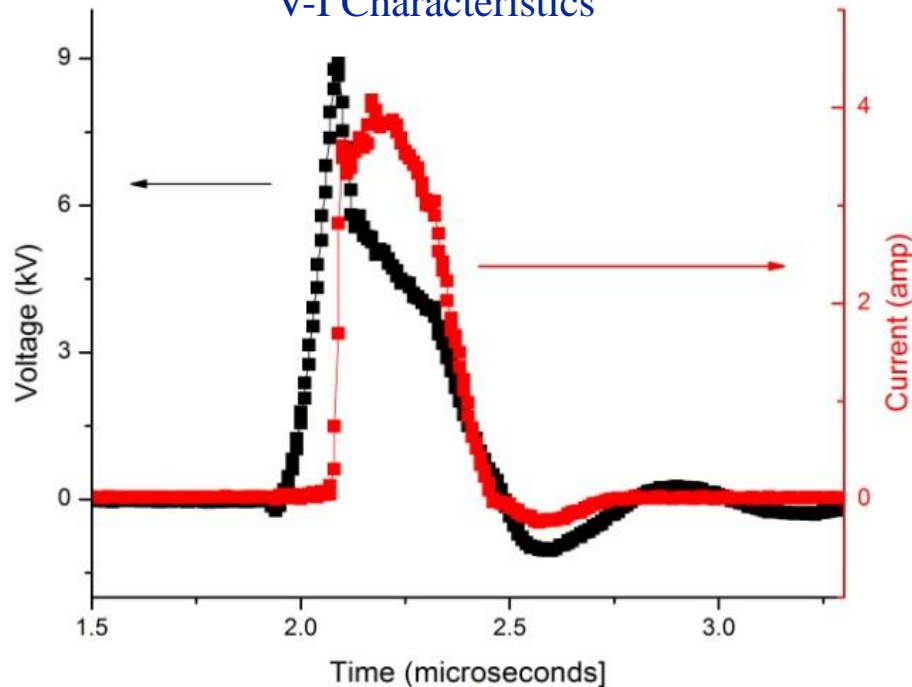


Non-thermal Plasmas to Modify Combustion Kinetics*



- **Goal:** Study effect of pulsed plasma on a C_3H_8 /air Bunsen flame
- Quantify with phase-averaged Raman scattering and CH chemiluminescence & time-resolved OH chemiluminescence

V-I Characteristics



*B. Ganguly, J. Schmidt (AFRL/RZPE)

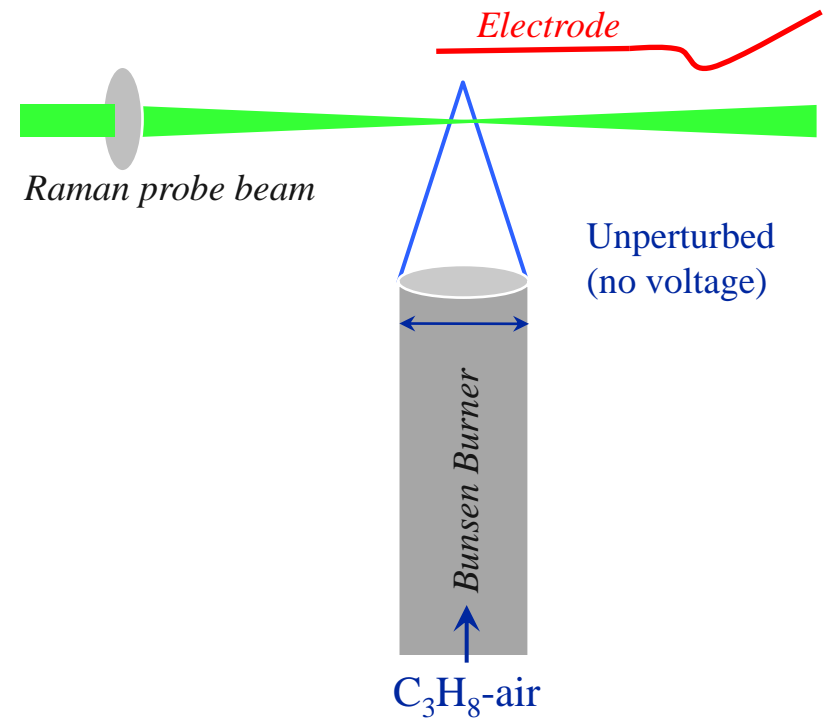
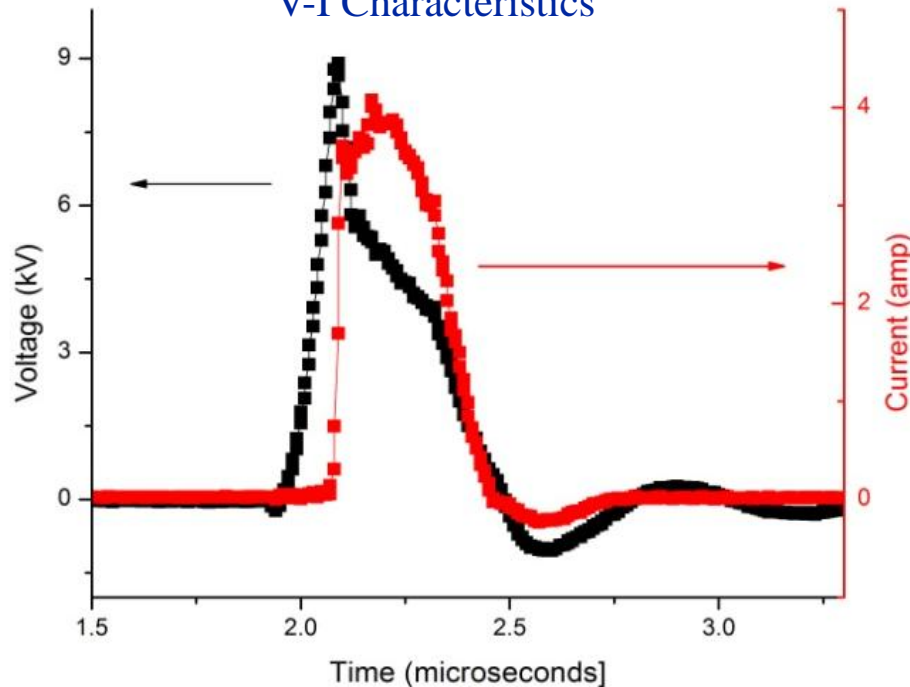


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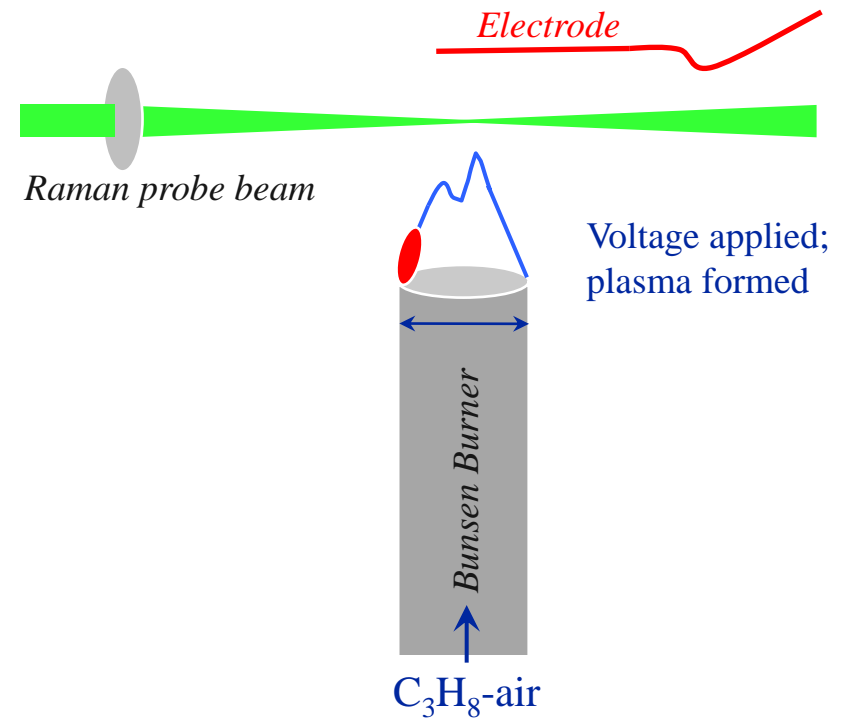
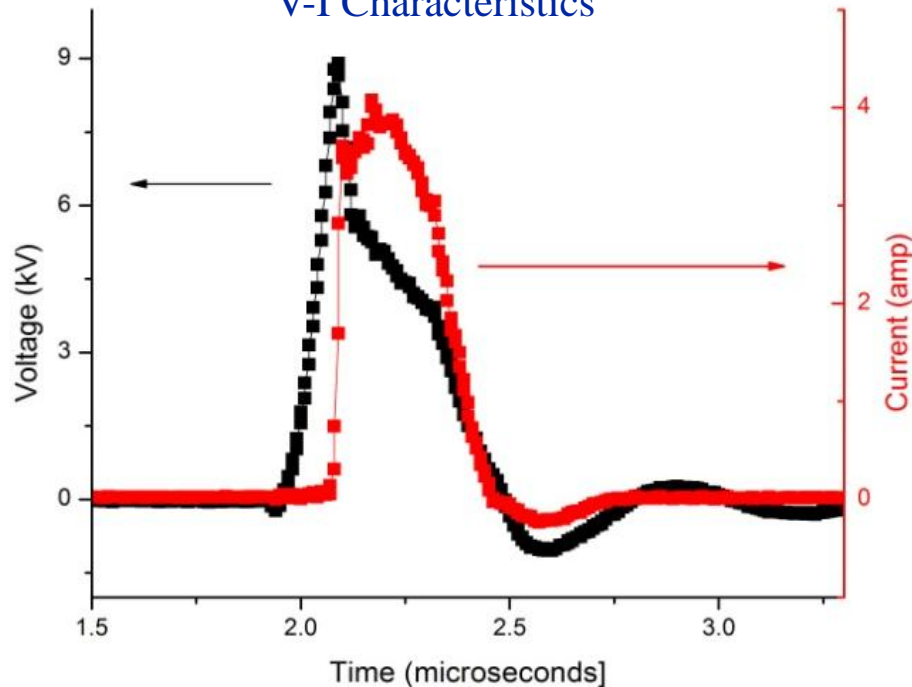


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V-I Characteristics





Non-thermal Plasmas to Modify Combustion Kinetics*



- 200 Hz rep rate pulsed discharge
 - Few mJ of energy input; significant perturbation
- Phase-locked measurement of T and CH chemiluminescence
 - Finite response of flame; some recovery before next pulse

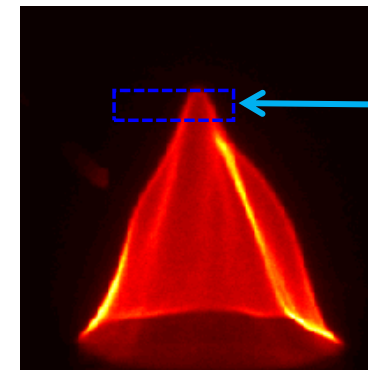
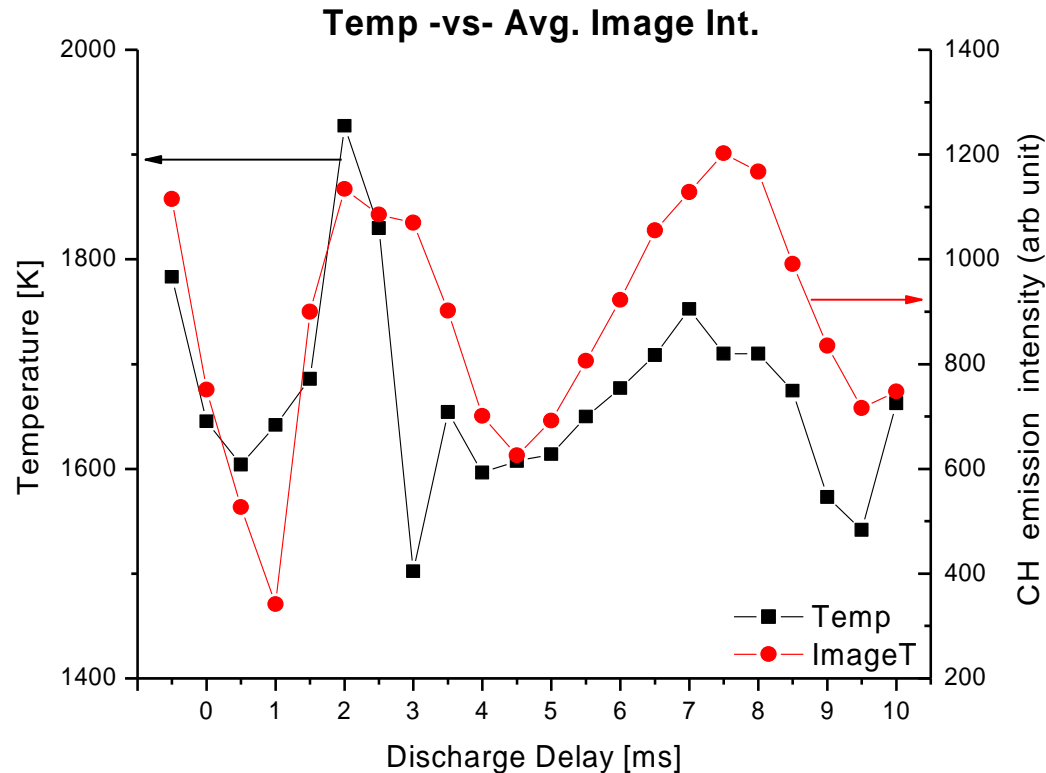
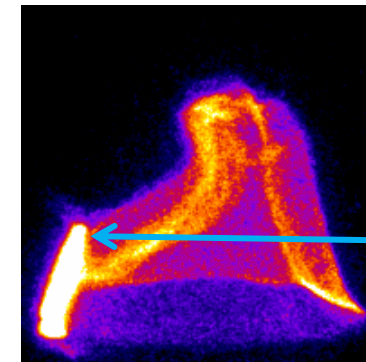


Image area (overlap
laser probe)



Flame perturbed
by pulsed plasma



Summary



Three final thoughts:

- Understanding the role of electric fields, plasma & *plasma-derived species* in initiating and sustaining combustion of critical importance to more effective use
 - Potential for impacting many areas related to use of hydrocarbons
- We (AFRL) welcome collaborations!
 - Many already with MURI team members
 - We'll even do some crazy stuff
- Good luck on efforts!